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By-Briggs, George E.

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A series of four experiments was performed based on a model of human information processing. The model postulates four stages in the processing of an external stimulus: encoding (stage 1), central processing (stage 2), response selection, e.e. decoding (stage 3), and response execution (stage 4). The total reaction time can be decomposed into two or more components which reflect the operation of these stages. It is argued that RT=A+B(Hc) where RT is total reaction time, A is the time taken for stages 1 and 3, B is the rate of central processing and Hc is an expression of the uncertainty associated with stage 2. Experiments based on this model investigated high speed scanning of random figures in human memory, retrieval time as a function of memory ensemble size, information processing as a function of speed versus accuracy, and memory retrieval and central comparison times in information processing. The results were consistent with the model, and it proved possible to quantify the rates of steps involved in the stages. (EB)

AND UNCERTAIN…

REACTION TIME AND UNCERTAINTY IN HUMAN INFORMATION PROCESSING

by

George E. Briggs

TECHNICAL REPORT NO. 69-5

On Work Performed Under

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The Ohio State University
Columbus, Ohio 43210

FOREWORD

This report is the result of research conducted on human information processing supported in part by Grant Number GN-534 from the Office of Scientific Information Service of the National Science Foundation to the Computer and Information Science Research Center, The Ohio State University.

The Research Center is an interdisciplinary research organization which consists of the staff, graduate students, and faculty of many University departments and laboratories. This report presents research accomplished in cooperation with the Human Performance Center, Department of Psychology.

The research was administered and monitored by The Ohio State University Research Foundation as Project 2218-A.

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INTRODUCTION

Hick (1952) was one of the first psychologists to make use of Shannon's (1948) development of information concepts and measurement methodology in the study of man as an information processor. Specifically, Hick showed that there was a linear relationship between reaction time (RT) and information transmitted in a choice reaction time task. He originally stated the relationship as

$$RT = K \log (n_e + 1) \qquad \text{Eq. 1}$$

where n_e is the equivalent degree of choice calculated from Shannon's information transmitted (H_t) metric, K is the proportionality constant, and the addition of unity to n_e was rationalized as an expression of temporal uncertainty in the task—when will a signal occur?

Following Hick's classic paper, others, including Crossman (1953, 1955), Hyman (1953), and Bricker (1955), demonstrated the generality of the above relationship. Moreover, the statement of the relationship was expanded from that provided by Hick to the following form:

$$RT = A + B (H_t) \qquad \text{Eq. 2}$$

In this form _A_ was interpreted originally as a simple reaction time while _B_, or more properly its inverse, was interpreted as the rate of processing information in units of bits per second. The above interpretation of the intercept constant A has since been shown to be inadequate, and, indeed, Sternberg (1967) apparently was the first to give it the presently accepted interpretation: _A_ represents total stimulus encoding and response decoding time. It is seen, therefore, that Eq. 2 is a modern expression of Donders' (1868) additivity principle in reaction time: Total reaction time can be decomposed into two (or more) components. Further, these components reflect the operation of several different stages in the processing of information through the human operator. Smith (1968) summarized the basic research on choice reaction time and offers the following four-stage model: (1) Stimulus information is encoded; (2) that information is passed to a central processor wherein encoded input information is compared with memorial representations of possible stimuli; (3) from this comparison (stimulus identification) operation a response is selected (decoding); and (4) that response is executed. Stage 4 (response execution) is of little consequence in reaction-time studies as the measure of time begins with the onset of the stimulus and ends with the onset of Stage 4. Thus, the constant _A_ of Eq. 2 is interpreted today as the total time required by Stages 1 and 3 in the above model, while _B_ is the time occupied in Stage 2, in units of seconds per bit of information transmitted.

Figure 1 is a model of the sequential stages of human information processing as proposed by Smith (1968) and others. The research to be

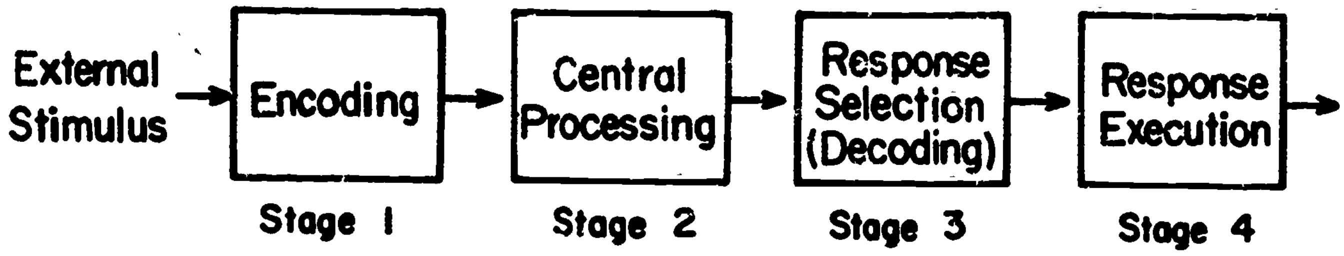


Fig. 1. A basic model of human information processing (after Smith, 1968).

reported herein will permit an elaboration of Stages 1 and 2 and these will be noted by additional figures in the text: Figure 13 in the General Discussion section, below, represents a more complete model derived via data from Figure 1.

An Alternative to Equation 2

Hick's law is a statement of the relationship between two dependent variables (two measures of human output): speed (RT) and accuracy (Ht). It is one of the most important statements in the literature on human information processing as it points out that the rate of gain of information through the human processor is constant. Therefore, it states that the human can trade speed for accuracy since these two dependent variables are proportional. But important as is Eq. 2 to our understanding of the human as an information processor, it is not an appropriate statement by which to infer the component processing times as in Smith's (1968) four-stage paradigm, above in Figure 1. What is needed for this purpose is a statement relating RT to an independent variable, the latter being under the experimenter's control.

The following is proposed as a more appropriate statement of additivity in human information processing:

$$RT = A + B\,(H_c) \qquad \text{Eq. 3}$$

where H_c is a Shannon expression of the uncertainty associated with the central processing stage of the Smith paradigm (Stage 2). This uncertainty is defined by the task conditions, primarily memory load, which the experimenter chooses. For example, in the information-conservation task used by Hick (1952) the experimenter provided a set of stimulus lights and he assigned to each stimulus a different response key. Hick varied memory load systematically by presenting separately series of choice reaction-time trials on ensembles of 2, 3, 4, 5, 6, 8, and 10 lights. Given a particular ensemble condition, say four lights, the subject was required to identify the occurrence of a particular light (and thus determine the appropriate response) by reference to a memory ensemble containing representations of the four possible stimuli. Thus, stimulus uncertainty (H_s) directly determined central processing uncertainty H_c in Hick's task (as it does in all information-conservation situations). Indeed, in those tasks the subject is required to perform a 1:1 mapping of stimuli on to responses, and so stimulus uncertainty, central processing uncertainty, and response uncertainty (H_r) are equal to one another.

However, in an information-reduction task, such as that used herein for Experiments I, III, and IV, it is not necessarily true that $H_s = H_r = H_c$. Further, if the subject can be induced (through instructions and a payoff matrix of rewards and penalties) to generate very few incorrect responses, then in an information-conservation task H_c and H_t are approximately equal, but in an information-reduction task such equality generally does not hold even for error-free performance.

Why, then, pick H_c as the basic predictor variable in Eq. 3? Both H_s and H_r also are under the control of the experimenter. The reason offered here is that H_c is determined by both H_s and H_r and neither of the latter alone provides a complete definition of the number of possible outcomes of central processing in an information-reduction task. Therefore, for maximum generality across both information-conservation and reduction tasks (both of which have been used extensively to study human information processing), it is recommended that H_c be the basic predictor variable for RT as in Eq. 3.

H_c is defined as $\sum_{i=1}^{m} p_i \log p_i$ where p_i is the probability of the i^{th} outcome of central processing and the summation is across all m possible outcomes. As such, it is an index to the number of steps required to complete central processing, or in terms stated by Welford (1960, p. 197) it is "the equivalent number of equi-probable choices" at Stage 2 of the Smith (1968) paradigm. This interpretation is important in light of Fitts' hypothesis (1959) whereby he suggests that as the number of steps between stimulus and response increases, there should be an increase in number of errors and in the time required to operate upon stimulus information in order to determine and thus emit a response. H_c is an index of such a number of steps within Stage 2, which is the stage where logically the experimenter is free to vary the number of steps (complexity) of information processing.

Summary

Hick's law provides us with the intriguing notion that the slope constant B is an index to central processing time. It is argued that one would be better advised to use the statement

$$RT = A + B\,(H_c) \qquad \text{Eq. 3}$$

as the basic expression of additivity in human information processing. We may predict (and Experiment III will verify) that H_t is a parameter of Eq. 3. We will identify Eq. 2 as Hick's law and Eq. 3 will be called a Hick relationship.

GENERAL METHODOLOGY

Stimulus Materials

In each experiment it was desirable to control for preexperimental familiarity with the stimulus materials. Therefore, random figures were selected which also permit control over association values. These figures were generated by a computer program made available by Vanderplas, Sanderson, and Vanderplas (1965). The figures so generated were photographed on 35-mm. film and mounted on 2 x 2 inch slides. Figure 2 shows a representative sample of four such random figures. Upper left and right are a four-sided and a six-sided figure, while an eight-sided and a ten-sided figure are shown bottom left and right, respectively.

Apparatus

The subject sat 2 feet from an opaque screen on which was back-projected a series of stimulus slides. He wore a headphone set with

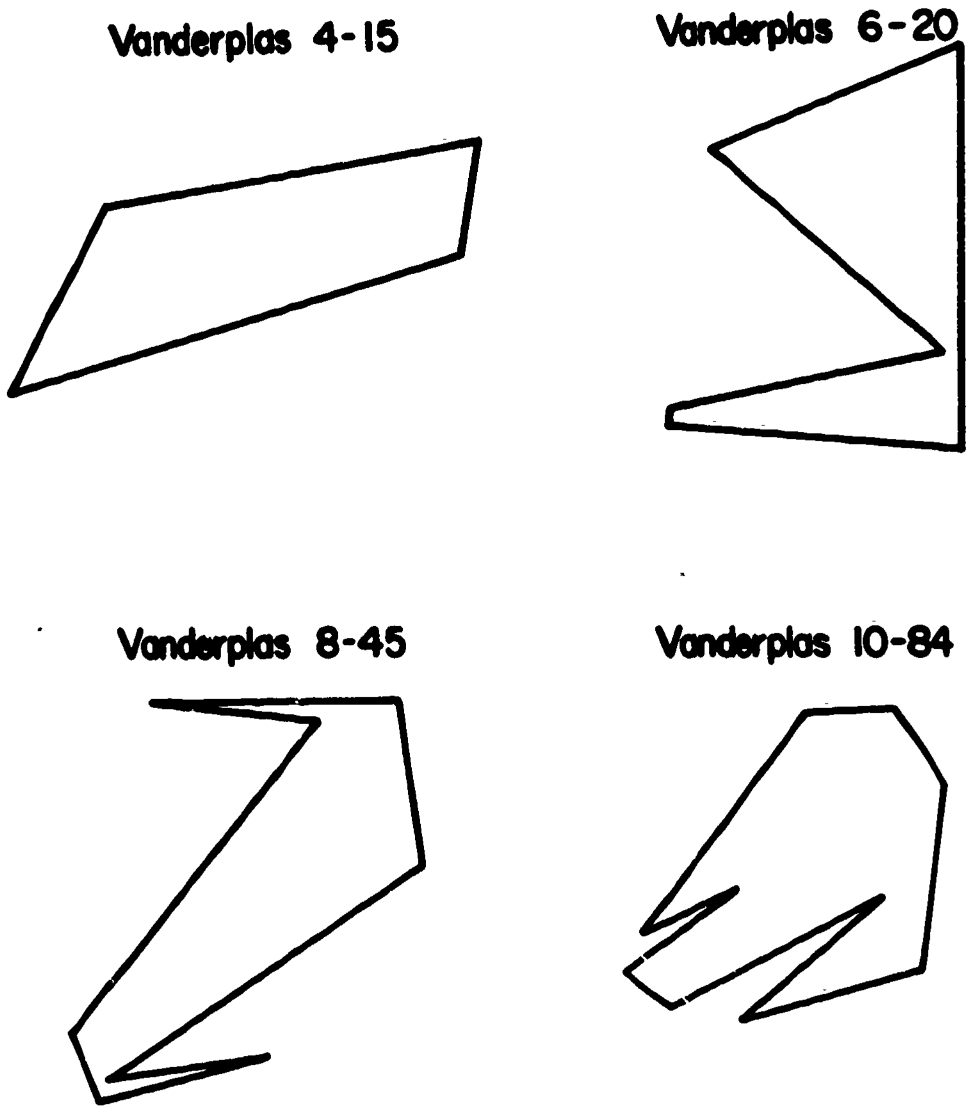


Fig. 2. Examples of Vanderplas random figures used in the present research as stimulus items.

an attached boom microphone. A broadband white noise was present at the earphones at all times except when the experimenter wished to communicate with the subject. The auditory noise masked other potentially distracting sounds in the laboratory. Electronic timers controlled the onset and duration of stimuli on the screen. A shutter was placed between the projector lens and the screen, and a photoelectric diode was placed between the shutter and the screen. Upon shutter opening the diode was activated which in turn started a Hewlett-Packard 52236 electronic timer. The timer operated at the rate of 10,000 counts per second until shut off by a Schmitt trigger that was activated by any vocal response by the subject. The experimenter recorded the accuracy of each response and the time indicated between stimulus onset and response onset, the reaction time (RT).

Procedure

A given subject would participate in daily 30-minute sessions for from one to six weeks depending on the experiment. An initial one or more sessions were devoted to familiarization training with the stimuli and the task. Typically a subject would receive summary feedback on his performance at the end of each session. In addition to this summary feedback, the subjects in Experiment III, below, received immediate feedback after each response.

Once familiar with the stimuli and the task, the subject would see a series of slides. He was required to respond vocally to the slides. In Experiments I, III, and IV he was to categorize each test stimulus into one or the other of two categories: "yes" the stimulus matches one in memory or "no" it does not match a memory item. This was an information-reduction task. Experiment II utilized an information-conservation task in which the subject learned and utilized a unique vocal response (name) for each individual stimulus.

Each subject was randomly assigned to experimental conditions following his response to an ad which appeared in the campus paper. Each was paid at the rate of $1.25 per session, and in Experiments II, III, and IV a subject could increase his earnings via a bonus system.

EXPERIMENT I
HIGH-SPEED SCANNING OF RANDOM FIGURES IN HUMAN MEMORY[1]

This was planned as a preliminary experiment in the series. It was intended to determine if a Hick relationship would hold in the information-reduction task planned for later experiments, and we desired

[1] This study served as a MA thesis for Mr. Larry T. Bashark. The thesis is on file at the Ohio State University Library, 1968.

to determine if the random figures could be memorized and responded to appropriately by the subjects.

Method

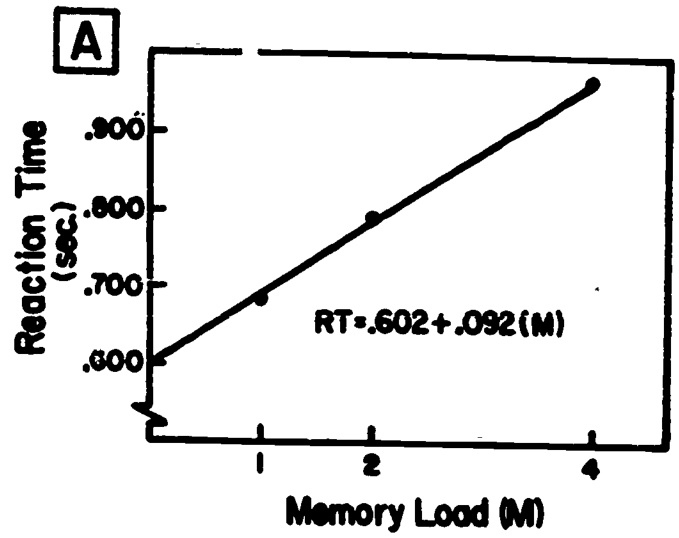
Eight male and eight female subjects participated in the study. Each experienced two sessions involving the information-reduction task, and then after an interval of five weeks, each subject participated in another two sessions on the task of interest. We will identify the two sets of sessions as pretest and posttest, respectively. During the five-week interval the same subjects served in a pilot study for Experiment II to be reported below. For the current study our only interest in the work performed during the five-week interval is that it involved some rather large ensembles of some of the same stimuli and of stimuli similar to those used in the information-reduction task. This fact will be of use in interpreting the results of the present study.

The Sternberg I (1966) procedure was used to define the information-reduction task. Here, each subject saw a series of one, two, or four slides each with a single figure, and then he saw a test slide with a single figure. He was to respond to the test slide either "yes" the test slide contains a figure in short-term memory of the preceding slide or slides, or "no" the test slide does not match a figure in short-term memory. Each series of slides will be identified as a trial. There were 60 trials per session. On 30 of the trials a positive response was appropriate while a negative response was appropriate on 30 trials. The sequence of these two response classes was randomized. Of the 60 trials there were 20 trials in which only one figure had to be retained in short-term memory, and 20 trials each for memory loads of two and four figures. These three memory loads were randomized across the 60 trials. Four-, six-, eight-, and ten-sided figures were used equally frequently as both memory and test stimuli.

In the case of the lowest memory-load condition (one figure in memory), the probability of a test figure matching the figure in memory was $p = .50$ while the probability of no match was $p = .50$; thus, $H_c = \Sigma\, p \log_2 p = 1.0$ bit for this condition. For the next memory-load condition (two figures in memory), each figure was matched by the test stimuli with $p = .25$ while again no match occurred with $p = .50$; therefore, $H_c = \Sigma\, p \log_2 p = 1.5$ bits. Finally, $H_c = 2.0$ for the condition in which four figures were carried in memory (the probability of a match for each memory item was $p = .125$ while $p = .50$ for no match).

Results

Across each set of two days each subject experienced each memory-load condition 40 times. For 20 of these trials a positive response was correct while a negative response was correct within each memory-load condition on 20 trials. A median RT was determined for the 20 trials within each memory load - response class condition, and then an



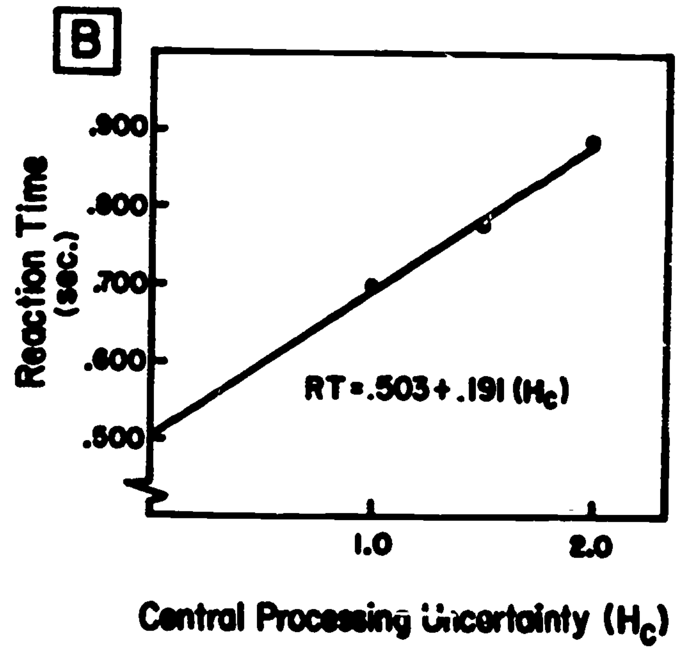


Fig. 3. Results from Experiment I
for pretest (A) and posttest (B) sessions.

average across subjects and across response classes was obtained for each memory-load condition. The pooling across response class was justified by the finding of no statistically significant difference between positive and negative response RTs. This was the same result obtained by Sternberg (1966) in a comparable task.

The average RT data are summarized in Figure 3a for the pretest sessions and in Figure 3b for the posttest sessions. It is apparent that a Hick relationship holds for the posttest data in the form of that statement provided by Eq. 3:

$$RT = A + B\,(H_c)$$

However, for the pretest data there is a linear rather than a log relationship between RT and memory load:

$$RT = A + B\ (M)$$

This somewhat surprising result will be discussed below.

Best-fit equations are listed in the figure and one may note that despite the difference in the form of the RT-memory load relationship, there are very good fits for each equation. This suggests, then, that random figures can be processed by the subject in as lawful a way as with less complex stimuli such as the lights used by Hick (1952). We were encouraged, therefore, to utilize such random figures in our subsequent studies.

It should be noted from Figure 3a that the central processing time index, B, was substantially slower than that found by Sternberg (1966) using an identical procedure but with arabic numerals as stimuli. After an amount of experience comparable to that in the pretest, Sternberg's subjects provided an average slope constant of 38 msec. per item of memory. This was over twice the processing time found here in the pretest data: 92 msec. per item in memory. This suggests that in the use of random figures in later experiments we could expect to find slow processing times unless the subjects are given extended training (familiarization) with these stimuli. Parenthetically it may be noted here that the processing time indicated in Figure 3b also is quite slow compared not only to earlier studies but also to the results found in this program (see Experiment III, below).

Discussion

We were encouraged by these results in the use of Vanderplas random forms for the subsequent experiments. There apparently is a relatively simple, lawful relationship between RT and memory load as previously noted for such diverse but previously familiar stimulus materials as lights, decks of cards, pictures, etc. The form of the relationship appears to be somewhat variable with the random figures: In the pretest the form was linear whereas in the posttest it was logarithmic.

Now, these two forms of the RT-memory load relationship both permit the same interpretation of the intercept and slope constants: A represents encoding and decoding time while B represents central processing time. A linear form of the relationship indicates that central processing proceeded in a strictly serial manner (Sternberg, 1966, 1967) while a log relationship suggests a more efficient series of steps in central processing wherein each step eliminates a larger number of possibilities than the single possibilities indicated in the linear form of the relationship (Hick 1952).

It is logical that one would find a linear relationship in the pretest and a log relationship in the posttest. Welford (1960) pointed out that for a memory load of up to eight items it is just as efficient to consider each memory item in turn as it is to engage in, say, a successive dichotomizing process whereby half the possible memorial representations are eliminated by the first step, half of the remaining are eliminated by the second step, and so on. However, for memory loads greater than eight items, the successive dichotomizing process would be more efficient than a one-by-one series of tests of encoded information with memorial representations of possible stimuli.

Now in the pretest, each subject never had to store more than four stimuli in short-term memory at any time and so like those subjects in Sternberg's study (1966) it is not surprising that our subjects showed evidence of a strictly serial, one-by-one comparison of test stimulus to memorized stimuli. But why a log relationship for the posttest data? After all, each subject still did not deal with more than four stimuli in memory at any given time.

It is suggested that the experience of each subject during the five-week interval between pretest and posttest accounts for the change in the processing mode noted for the information-reduction task. As indicated earlier, during the five-week interval the subjects dealt extensively with rather high memory loads: They memorized and utilized memory ensembles of 2, 4, 8, and 16 stimuli. Clearly, then, according to Welford (1960) we should expect our subjects to utilize a successive dichotomizing test strategy in their processing of information since memory load exceeds the eight-item limit, noted above. Otherwise, efficiency (speed in particular) would suffer especially with a memory load of 16 items should the subjects persist in a one-by-one serial test procedure.

There is evidence that the subjects do indeed utilize a successive dichotomizing test strategy during the task utilized in the five-week interval between the pretest and the posttest (see Experiment II, below), and so it is logical that they would transfer the same mode of central processing to the information-reduction task in the posttest sessions. Thus, the log relationship between RT and memory load observed in Figure 3b.

EXPERIMENT II
RETRIEVAL TIME AS A FUNCTION OF MEMORY ENSEMBLE SIZE[2]

Following Experiment I we felt that our subjects could process information from Vanderplas random forms in a reasonably efficient manner and that these forms could serve as stimuli in a study wherein it was essential to control for preexperimental familiarity. The present

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[2] This study has been accepted by the Quarterly Journal of Experimental Psychology with G. E. Briggs and J. M. Swanson as authors.

study was designed as a direct test of Oldfield's (1966) derivation of a relationship between the latency of naming responses and memory ensemble size.

Oldfield utilized data previously collected by Oldfield and Wingfield (1965) which showed an inverse but linear relationship between RT in a picture-naming task (information conservation) and the log frequency of occurrence of such names in textual materials. Oldfield supposed that memory for names may well be organized into ensembles with the largest ensemble containing the names least likely to be used in everyday tasks, a somewhat smaller ensemble for more frequently occurring names, and so on, with the smallest ensemble consisting of object names most likely to be encountered in everyday discourse. In other words, he felt that Zipf's law (1935) provided a key to the organization of human long-term memory for object names.

Oldfield therefore determined the form of Zipf's relationship for the names used by Oldfield and Wingfield including other equally likely names. From this relationship between log number of names and log frequency of occurrence he was able to infer the size of the memory ensembles used by the Oldfield and Wingfield subjects and to express observed vocal RT as a function of ensemble size (memory load). When so plotted, Oldfield found a linear relationship between RT and log memory load (M):

$$RT = .373 + .058 \log_2 M$$

This will be recognized as an instance of a Hick relationship. Oldfield interpreted the intercept constant in a slightly (but significantly) different way than others: He suggested that it includes not only encoding time but also the time required to select a particular memory ensemble for a subsequent search. By virtue of the log relationship, he suggested, like Hick, that that memory search consists of successive dichotomizing tests in order to match encoded stimulus information and memorial representations of possible stimuli. The rate of such processing is provided by the inverse of the above derived slope constant—17 bits per second.

In order to test directly the generality of a Hick relationship to a stimulus-naming task, it is clear that one must control for the familiarity of the stimulus material. As such, random-form stimuli were organized into four ensembles of sizes 2, 4, 8, and 16 figures. The subjects then learned a name (a letter followed by a two-digit number) for each of the 30 figures. This was accomplished via a series of paired-associate trials extending over four daily sessions. Following this preliminary training, each subject was repeatedly exposed to the stimuli one at a time for six daily sessions. The frequency of occurrence followed a Zipf relationship with each of the two stimuli in the smallest ensemble appearing eight times for every single occurrence of a stimulus from the largest ensemble, four times for every item occurrence from the second largest ensemble, and so on. Each time a stimulus figure occurred the subject was to pronounce its name as rapidly and as accurately as possible. These six sessions provided data to determine if a Hick statement would hold in the stimulus-naming (information-conservation) task wherein the relation between familiarity and ensemble size was controlled according to Zipf's law.

In a final session a special test was conducted to explore Oldfield's interpretation, noted above, of the intercept constant in a Hick relationship. If part of the intercept is due to the time required to select a memory ensemble for subsequent processing, then the intercept but not the slope constant should be decreased if the subject is informed just prior to the exposure of a stimulus of the particular ensemble from which the stimulus was selected.

Method

Four female and eight male subjects participated for 12 successive work-day sessions. An initial session familiarized the subjects with the 30 random figures to be used and with the ensemble groupings. This was accomplished by exposing the 30 figures singly and requiring each subject to name its ensemble. For half the subjects the smallest ensemble (a memory load of two figures to be designated $H_C = 1$ bit) consisted of two four-sided figures and the ensemble designation was the letter A; the $H_C = 2$ bits ensemble consisted of four six-sided figures with ensemble designation by the letter E; the $H_C = 3$ bits ensemble was identified by the letter I and consisted of eight eight-sided figures; and the $H_C = 4$ bits ensemble consisted of 16 ten-sided figures with an ensemble designation O. The other half of the subjects experienced ten-sided, eight-sided, six-sided and four-sided figures in $H_C = 1$ through $H_C = 4$ ensembles, respectively. Thus, upon an occurrence of a stimulus from, say, the $H_C = 3$ ensemble each subject was to pronounce the letter I as rapidly as possible. Practice on ensemble designation resulted in highly accurate performance.

During each of the five succeeding days, the subjects learned the full name assigned to each figure. Each name consisted of the ensemble letter (A, E, I, or O) followed by a two-digit number. Thus, the total name for a particular figure consisted of the ensemble designation plus the specific (and unique) name of the figure. It follows that ensembles were distinguished on the stimulus aspect by sidedness and on the response aspect by the letter portion of the full name. During these five days of preliminary training Zipf's law was observed as much as possible. Thus, each figure in $H_C = 1$ occurred eight times for every single occurrence of a figure from $H_C = 4$, four times for every figure in $H_C = 3$, twice for every occurrence of a figure from $H_C = 2$, and so on. This inverse relationship was violated on the last session of preliminary training when the subject responded only to stimuli from the $H_C = 3$ and $H_C = 4$ ensembles. It was felt necessary to give extra practice on these two largest ensembles in order to prevent an inordinate number of errors in the data collection sessions to follow.

During the preliminary training sessions each subject observed a series of pairs of slides. First a stimulus figure would appear alone for 2 seconds and then the stimulus figure and its assigned name would appear for 2 seconds. During the initial 2-second period each subject was to pronounce the figure name, if possible. After the second 2-second period another stimulus figure appeared and so on.

Following the five preliminary sessions, each subject participated in six sessions to provide the experimental data. These will be identified as the differential learning sessions, and the subjects experienced the same task as in the preliminary sessions except that the Zipf relationship between familiarity and ensemble size was adhered to strictly throughout the period. Reaction times and errors were recorded by the experimenter for each stimulus occurrence. A bonus payoff system was introduced at the beginning of the fourth differential learning session to maintain subject motivation in this task. The payoff matrix emphasized both accurate and speedy responses.

On the twelfth and final session the subject first experienced figures from the four ensembles in the same way as in the previous six sessions of differential learning. Following this, a special test was performed. Here the experimenter notified the subject of the ensemble from which a figure was drawn just prior to exposure of that figure. Thus, in the special test the experimenter might say: "The next figure is an A figure." Then the subject merely gave the digit portion of the name upon stimulus occurrence, e.g., "24." This is in contrast to the normal test just preceding wherein no advance information was given and the subject was required to pronounce the full name, e.g., "A-24," for each stimulus upon its occurrence.

Results

During the preliminary training sessions (and also in the subsequent sessions as well), it was noted that vocal responses starting with the letter E (the H_c = 2 stimuli) often did not stop the electronic counter at the onset of the vocalization. This was not observed for responses starting with the letters A, I, or O (the H_c = 1, 3, and 4 ensembles, respectively). Therefore, the H_c = 2 ensemble data were excluded from data analysis as they were artifactually slow as recorded. (The problem was located in the Schmitt trigger which was not sensitive to a relatively soft E pronunciation.)

Figure 4 provides a summary of the results in terms of average RT for ensembles H_c = 1, 3, and 4. It may be noted that data from differential learning sessions 1 and 4 are not included in the figure. Just prior to the first differential learning session, Zipf's law was violated, as indicated above, and it was desirable to examine results only after that relationship had been reestablished as in the first differential learning session. Data from the fourth differential learning session were not considered as this was the first session under the

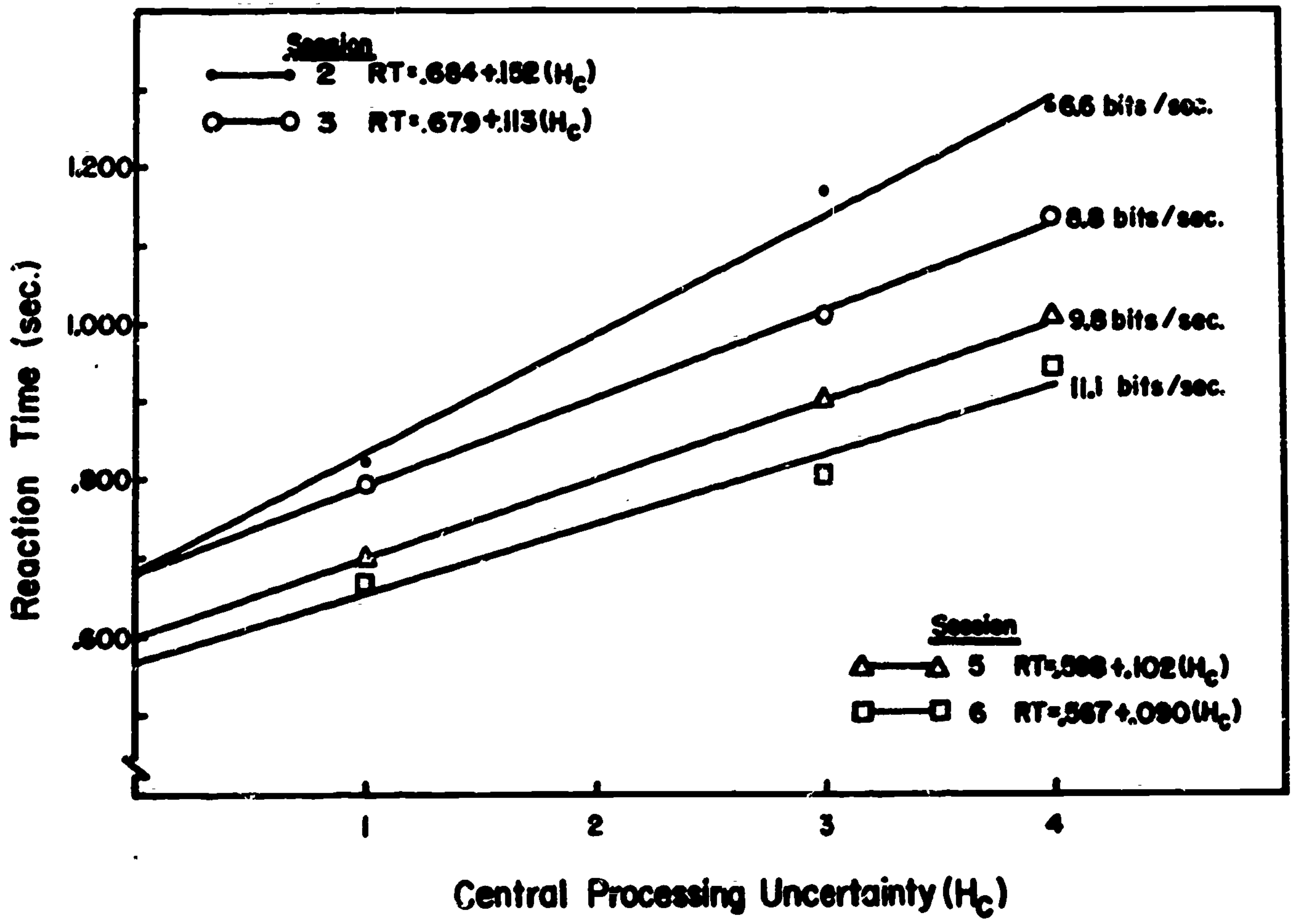

Fig. 4. Results from the differential learning sessions of Experiment II.

bonus system, as indicated above, and it was desirable to consider results only after that period of adjustment.

It may be noted from Figure 4 that a Hick relationship does indeed hold in this situation. There is a linear function relating H_C to RT with the general equation being

$$RT = A + B\ (H_C) \qquad \text{Eq. 3}$$

This confirms Oldfield's derivation and lends support thereby to his interpretation that memory for object names is organized in terms of ensembles where the size of ensemble follows Zipf's law. The results also show that with practice both the intercept constant A and the slope constant B decrease. Thus, with practice, subjects become increasingly efficient in encoding and decoding (the A constant) and in the central processing of encoded information (the B constant). It should be noted that the rate of central processing did not approach too closely that derived by Oldfield for previously familiar stimuli (17 bits per second). However, our subjects progressed monotonically from a rate of 6.6 bits per second on the second session to 11.1 bits on the sixth session. Therefore, with even more extensive practice, there is evidence that our subjects could have approached closely the central processing rate noted by Oldfield.

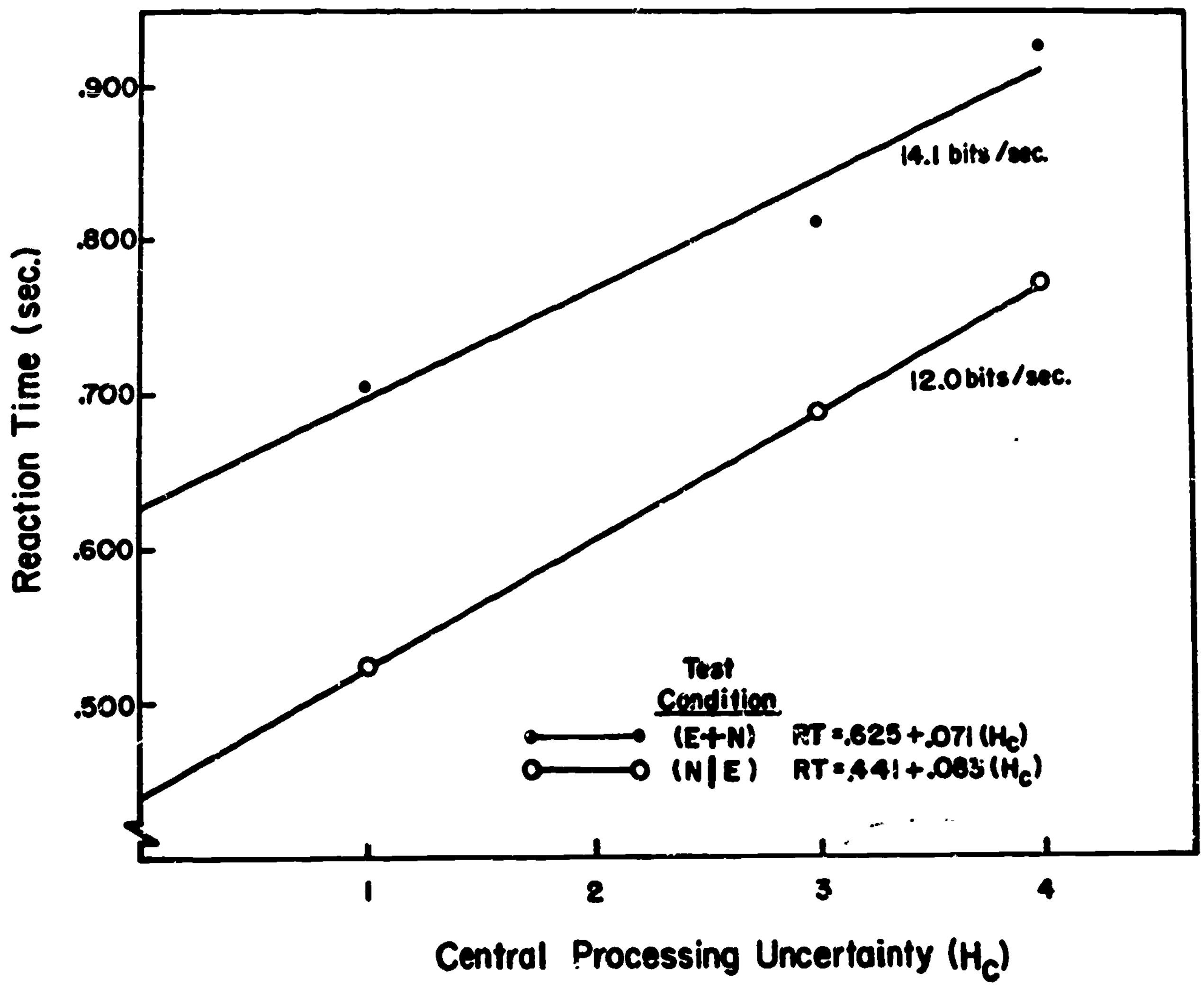

Fig. 5. Results from the special test session of Experiment II.

To this point, then, the present data merely confirm Oldfield's derivation and show, therefore, that a Hick relationship holds in this task. What about Oldfield's suggestion that the A constant includes ensemble selection time in addition to encoding and decoding time? The results of the special test session speak to this issue, and those results are summarized in Figure 5.

The results in Figure 5 for the upper function (test condition E + N) were determined from the first half of the special test session wherein a subject received no advanced information from the experimenter on the stimuli prior to their individual exposure. The bottom function (N|E) represents the data wherein the experimenter announced the ensemble designation for each stimulus just prior to stimulus occurrence and the subject was required only to emit the digit portion of each name (name given ensemble). As in Figure 4, it is obvious that a Hick relationship was obtained in both test situations. Further, while there is a statistically significant difference overall between these two sets of data, there is no statistically reliable difference in the slopes of the two functions.

Therefore, these results confirm Oldfield's suggestion that the A constant of Eq. 3 includes ensemble selection time in addition to encoding and decoding times: Knowing the ensemble prior to stimulus occurrence obviates the need to select the ensemble subsequent to stimulus occurrence and saves, therefore, approximately 184 msec. in total RT (the difference between the intercept constants of the equations listed in Figure 5).

Discussion

The latter result noted above is quite instructive to our understanding of human information processing. Specifically, the influence of advanced information on ensemble designation was with regard to the A constant, and it had no influence on the B constant. In terms of the sequential model of information presented earlier (see Figure 1), this means that Stage 1 includes not only the encoding of stimulus information but also some mechanism capable of performing a rudimentary analysis of the encoded information so as to ascertain its "familiarity" which in turn can key the appropriate long-term memory ensemble for subsequent search in Stage 2.

It is interesting to note that in a rather different kind of information-processing task, Sperling (1967) suggests the need for what is called a recognition buffer memory between a store for initially encoded stimulus information and the central processing stage. Sperling suggests that in his task (a recognition task utilizing short-term memory) the recognition buffer memory mechanism merely keys certain stimulus rehearsal programs. Our present results suggest that such a mechanism also can key long-term memory ensembles for subsequent search.

Therefore, it appears desirable to expand Stage 1 as shown in Figure 1 to include a recognition buffer memory mechanism. This has been done in Figure 6. As suggested by Sperling, this buffer is placed between the initial store of encoded visual information, iconic storage in Neisser's (1967) terms, and Stage 2 operations. It may be noted in Figure 6 also that a SCAN mechanism has been placed between the iconic store and the recognition buffer memory component of Stage 1. This too follows Sperling's basic model and while the need for the

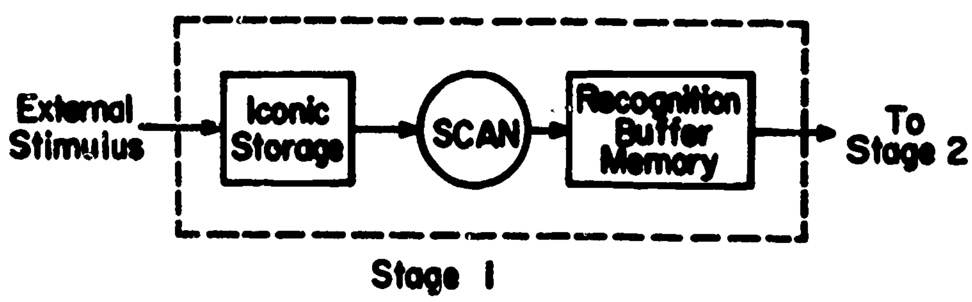

Fig. 6. An expansion of Stage 1 from Figure 1 (after Sperling, 1967).

SCAN mechanism is not indicated in the present study, the results of Experiment III, below, clearly justify its presence in the model.

Therefore, we may identify several subprocesses in Stage 1 of the basic sequential model of human information processing. A stimulus occurs; information from that stimulus is encoded and held momentarily in a short-term store—the icon; a SCAN mechanism samples the icon and transmits such sampled data to a recognition buffer memory where a preliminary analysis establishes the particular ensemble in long-term memory which is to be used in Stage 2. This completes Stage 1 operations. Stage 2 operations then proceed with a series of comparisons or tests relating encoded stimulus information sampled in Stage 1 with memorial representations of possible stimuli from the ensemble selected in Stage 1. The nature of the Stage 2 operation does not involve a simple sequence of one-by-one comparison or tests involving each item of the ensemble in turn; rather, the log relationship shown in Figures 4 and 5 suggest that in this study the subjects engaged in a series of dichotomous eliminations of possible ensemble items. Thus, a first test could eliminate half of the ensemble items, a second test could eliminate half of the remaining ensemble items, etc., until all but one ensemble item had been eliminated. That item, then, provides a match between encoded and memorial representation and thereby identifies the stimulus. This completes Stage 2 of the model. Stage 3 consists of a selection of the appropriate response, given the outcome of Stage 2, and finally that response is executed in Stage 4.

From the best-fit equations in Figure 5, we may conclude that under normal testing conditions (the E+N function) our subjects on the average required 625 msec. to complete Stage 1 and Stage 3 operations during this final session. If one eliminates the familiarity estimation function of the recognition buffer memory component of Stage 1, total encoding and decoding time decreases to 441 msec. (the N|E function); thus, 184 msec. represents the approximate time taken by the buffer memory component to complete the familiarity assessment under normal testing trials. Once Stage 2 began, it proceeded at a processing rate of approximately 13 bits per second (the reciprocal of the average slope constant for the data of Figure 5) on this final session. Thus, central processing continued in the final session to approach the rate of 17 bits per second derived by Oldfield (1966).

EXPERIMENT III
INFORMATION PROCESSING AS A FUNCTION OF SPEED VERSUS ACCURACY[3]

Experiment II demonstrated the usefulness of identifying at least two components in the Stage 1 operations of Figure 1. As shown in Figure 6, Sperling (1967) has suggested that in addition to an encoding mechanism (the iconic storage device) a model of human information processing should include a SCAN mechanism to sample information from the icon and to load a recognition buffer memory.

The present experiment serves to examine the SCAN mechanism as a component of Stage 1. The study was designed around some theoretical contributions of Stone (1960). In that paper Stone considered the Wald (1947) concept of sequential sampling and the Neyman-Pearson procedure of deciding how much information to sample given preset levels of Type I and Type II errors. He developed thereby the first of several statistical decision models specifically applicable to choice reaction time tasks. Smith (1968) provides an excellent review of various statistical decision models developed by Stone and others and compares these with several other models in the explanation of empirical results from a number of studies involving information-reduction as well as information-conservation tasks.

One of the models developed by Stone, a fixed sample size model, was used to predict the relationship between processing time, processing uncertainty, and error rate. Expressed in terms utilized in the present paper, Stone's fixed-sample model predicts that RT will be a linear function of H_c and that there will be a family of such functions each parallel to the others with intercepts increasing as H_t increases, the latter being an inverse index of error rate. The present study provides an explicit test of this prediction.

All subjects experienced the same information-reduction task; however, half the subjects were instructed to achieve errorless performance, if possible, while half were instructed to make errors if necessary to achieve high-speed responses. These accuracy and speed instructions were supplemented by appropriate payoff matrices to reward a subject for either speed or accuracy. If Stone's prediction is confirmed, the RT-H_c function for the speed condition should have approximately the same slope constant, B, as for the accuracy condition, but the latter intercept constant, A, should be significantly higher (longer average RT) than that for the speed condition.

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[3] This study served as a MA thesis for Mr. James M. Swanson which is on file at the Ohio State University Library, 1969. A version of this study will be submitted to the Journal of Experimental Psychology for publication.

Method

Twenty-four males and 24 females served in this study for five daily sessions. Each was assigned randomly to one of four groups with the restriction of equal sex representation and a final total of 12 subjects per group. Groups 3A and 4A both worked under accuracy instructions and payoffs while Groups 3S and 4S experienced the speed condition. Groups 3A and 3S both utilized memory loads of 1, 2, and 4 items while Groups 4A and 4S both experienced memory loads of 1, 2, 4, and 8 items. The latter two groups were included to establish the form of the RT-memory load function more decisively than can be done with only three levels of memory load as in Experiment I, above.

The basic task was defined by the Sternberg II procedure (1966). Like the Sternberg I procedure described for Experiment I, the present procedure requires the subject to examine test stimuli and make either a positive response ("yes" that stimulus matches one in memory) or a negative response ("no" there is no match). However, whereas the Sternberg I procedure involved short-term memory, the Sternberg II procedure utilizes long-term memory: The subject thoroughly memorizes four ensembles of 1, 2, 4, and 8 stimuli (Groups 4S and 4A); he then sees a series of test slides half of which contain items from, say, memory ensemble 4, and he makes a positive or negative response to each slide as appropriate; later he would emit the same responses to a series of slides from each of the other ensembles. The subject always knows which memory ensemble is appropriate, but within a series he does not know whether a positive or negative response will be appropriate or which of the several possible positive set stimuli may appear next.

In this experiment eight-sided Vanderplas random forms were used. During Sessions 1 and 2 Groups 3S and 3A became thoroughly familiar with the seven forms to be used subsequently. They also were shown the three ensemble groupings. Groups 4S and 4A experienced the same familiarization training but did so with a total of 15 figures and the four ensemble groupings. The familiarization training consisted of paired-associate trials involving the figures as stimuli and two-digit numbers as assigned responses.

Following the two days of familiarization training, each subject was introduced to the information-reduction task and given either speed or accuracy instructions and an explanation of the appropriate payoff scheme to be used. This third session was considered a practice period, and Sessions 4 and 5 were devoted to formal data collection. In each of these latter two sessions each subject in Groups 3S and 3A experienced 32 trials under each of the three memory-load conditions, while the subjects in Groups 4S and 4A experienced 32 trials per day under each of the four memory-load conditions. Within each block of 32 trials a subject saw a series of slides randomized with respect to the occurrence of positive set stimuli (to which he was to say "yes") and negative set stimuli (to which he was to say "no"). The latter set consisted of 16 eight-sided random forms never seen during familiarization training but with association values comparable to those of the positive set.

The payoff matrix employed for Groups 3A and 4A provided a 1¢ bonus for each correct response but charged 20¢ for every error. The experimenter never mentioned response speed to these subjects; rather, he stressed response accuracy. The payoff matrix used for Groups 3S and 4S emphasized response speed instructions as follows: A subject received 1¢ for every correct and fast response, but he was charged (a) .1¢ for every fast-incorrect response, (b) .5¢ for every slow-correct response, and (c) 1¢ for every slow-incorrect response.

An immediate display of bonuses and penalties was placed below the visual display in front of the subject and after every response the experimenter indicated the amount of bonus or penalty accrued on that trial. These were cumulated over the 32 trials of a block and then the payoff display was reset. The experimenter used a cut-off criterion to define fast versus slow RTs based on each subject's individual performance: He attempted to set the payoff to the subjects in Groups 3S and 4S in such a way as to provide equal error rates under each of the memory-load conditions.

Since within memory-load ensemble 1 there was a single memory item and since a match of that item was possible on half of each 32-trial sequence devoted to that memory load, $p = .5$ and $p = .5$ for no match and so $H_c = p \log p = 1.0$ bit; memory-load ensemble 2 found each of the two items matched on one-fourth of the trials devoted to that ensemble, thus $p = .25$ for each item and so $H_c = \Sigma\, p \log p = 1.5$ bits; likewise, $H_c = 2.0$ and 2.5 bits for memory ensemble sizes 4 and 8, respectively.

Results

The RT data for positive and negative responses were pooled, a median for each subject was calculated for each memory-load condition on Sessions 4 and 5, and an average across subjects and sessions was calculated. These results are summarized in Figure 7a for Groups 3S and 3A and in Figure 7b for Groups 4S and 4A.

It is apparent from Figure 7 that again a Hick relationship has been found to hold: Each function has the basic form

$$RT = A + B\,(H_c) \qquad \text{Eq. 3}$$

The best-fit constants are listed in Figure 7a and 7b. As predicted from Stone's (1960) model, the set for speed versus accuracy influenced the A constant but not the B constant. Therefore, we may interpret the higher value of A for the accuracy condition as indicating that the subject took longer to complete Stage 1 operations under this condition than did subjects working under the speed condition. However, once Stage 1 was completed, central processing (Stage 2) was carried out at about the same rate under a speed condition as in an accuracy condition.

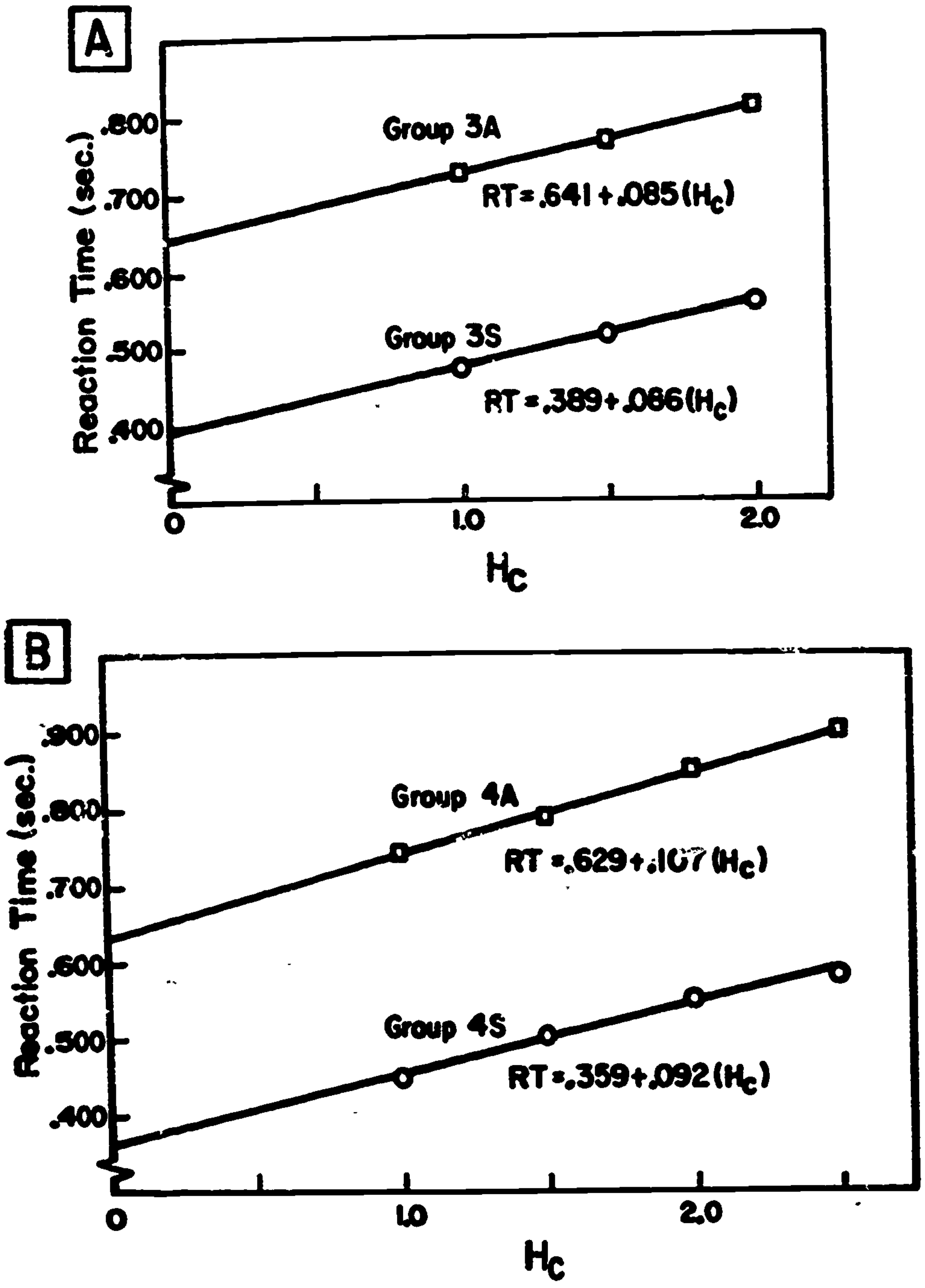

Fig. 7. The results of Experiment III.

These observations are confirmed by analyses of variance applied to the data: Overall, Group 3S was significantly faster than Group 3A ($p < .01$) but the interaction of groups by H_c was not significant ($p > .05$); thus, the two slope constants do not differ significantly. Strictly comparable results were obtained for Groups 4S and 4A in a separate analysis of variance.

The two speed groups generated an average of 9.4% erors while the accuracy groups generated an average of only .5% errors across the memory-load conditions.

Discussion

Further consideration may be given to the data of Groups 3S and 4S. The 24 subjects in these groups provided sufficient variation in accuracy to make it meaningful to examine the specific effect of error level on the A constant of Eq. 3. Only the data for memory loads of 1, 2, and 4 items (H_c = 1.0, 1.5, and 2.0 bits) will be considered as only these three conditions were common to both groups.

As a first step it is necessary to determine an index to error level. It was decided to utilize information transmitted (H_t) as the index. In this information-reduction task response uncertainty sets the upper limit (H_r = 1.0 bit) to H_t, and so H_t = 1.0 for error-free performance. As a subject commits more and more errors, H_t would decrease from 1.0 bit and approach zero bits.

As a second step it was desirable to normalize the basic RT-H_c functions to assure equal H_t for each of the three H_c conditions. This was accomplished in two stages. First, a plot of 24 RTs (one for each subject) was made for each of the three H_c conditions with H_t as the predictor variable. These plots are shown in Figure 8. Best-fit equations were then derived and these are listed in Figure 8 as are the correlation coefficients (all three being significant at $p < .05$).

Next, for each of the three H_c conditions values of H_t were substituted into the appropriate equation of Figure 8 to generate derived values of RT. This was done for five levels of H_t ranging from 0 bits to 1.0 bit. These normalized RTs are listed in Table 1. Also listed are best-fit equations relating RT to H_c for each of the five levels of H_t.

Table 1

Derived Values of RT for Three Levels of H_c Normalized Within Each of Five Levels of H_t and the Best-Fit Equations Relating RT to H_c

H_t	H_c 1.0	1.5	2.0	Normalized RT = A + B (H_c)
.00	.3527	.4021	.4592	RT = .245 + .106 (H_c)
.25	.3892	.4439	.4984	RT = .280 + .109 (H_c)
.50	.4297	.4857	.5376	RT = .322 + .108 (H_c)
.75	.4681	.5275	.5767	RT = .361 + .109 (H_c)
1.00	.5066	.5693	.6159	RT = .400 + .109 (H_c)

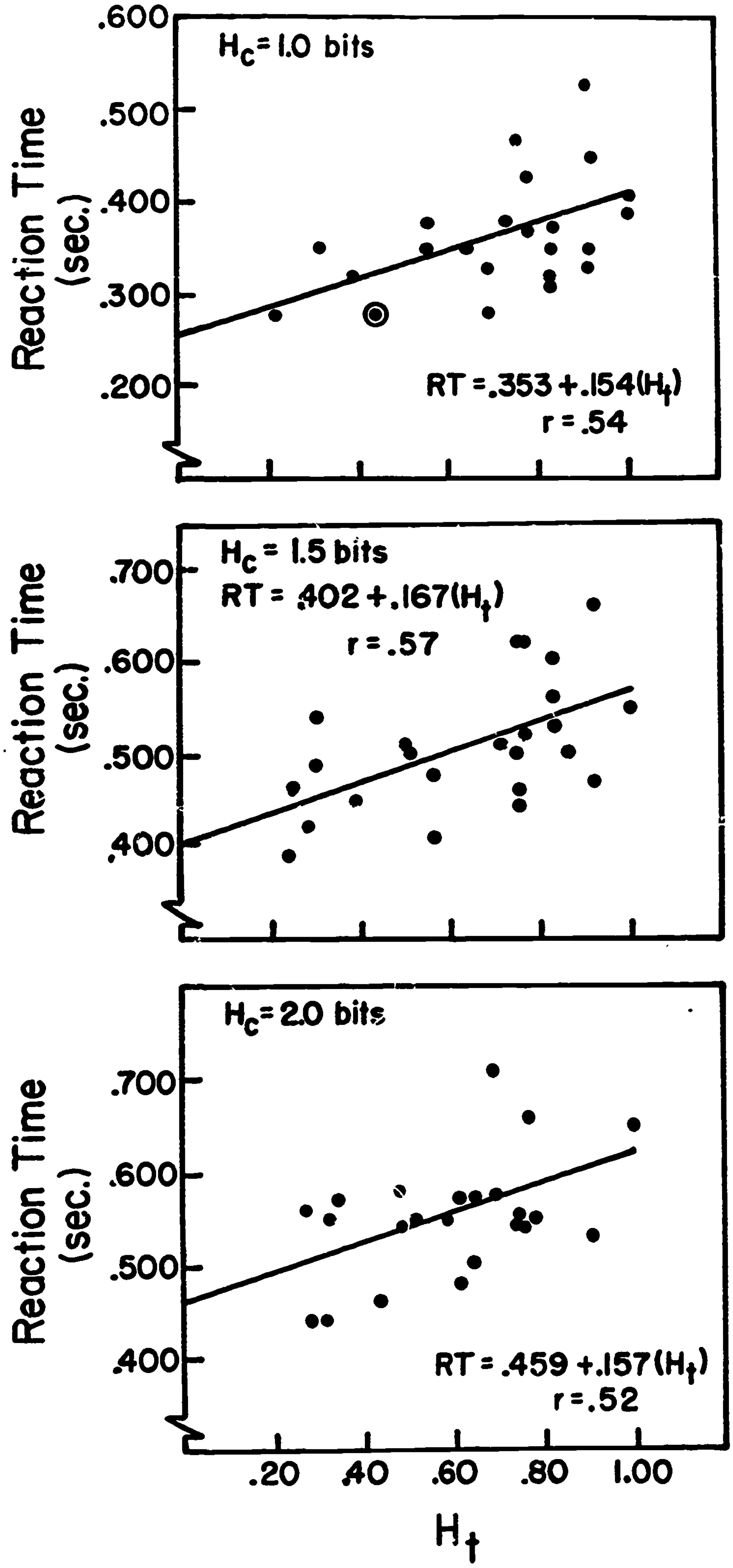

Fig. 8. Scatter plots for average data (median RTs) showing the relation of RT to information transmitted in Experiment III.

Table 1 contains the desired information: RT as a function of H_c with error level (H_t) as a parameter. Note that as expected a Hick relationship holds at each error level with comparable central processing times (B) for each error level but with a systematic decrease in the A constant as errors increase (as H_t goes to zero). The basic statement, then, from Table 1 is

$$RT = A + B\ (H_c) \qquad \text{Eq. 3}$$

Now, Figure 9 shows a plot of the A constant as a function of H_t. It can be seen that this also is a linear equation of the form

$$A = C + E\ (H_t) \qquad \text{Eq. 4}$$

Again, the best-fit equation is listed in Figure 9,

$$RT = .243 + .157\ (H_t)$$

Therefore, we may substitute Eq. 4 into Eq. 3 to obtain

$$RT = C + E\ (H_t) + B\ (H_t) \qquad \text{Eq. 5}$$

which fitted constants

$$RT = .243 + .157\ (H_t) + .109\ (H_c)$$

The B constant of 109 msec. is the average of the five slope constants from Table 1.

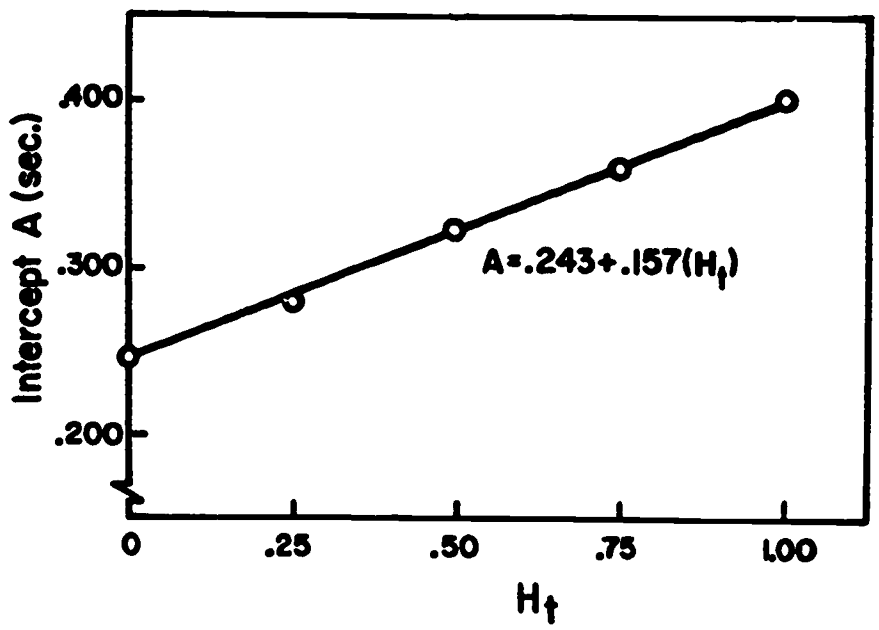

Fig. 9. The predicted relationship between the intercept constant A of Eq. 3 and information transmitted in Experiment III.

It follows, then, that we have shown it possible to separate the A constant of Eq. 3 into two components: C and E. Let us consider an interpretation of these two components. Now C is the intercept constant and so it represents total encoding and decoding time. But this represents only part of the Stage 1 time as E also was separated from the original A constant of Eq. 3. The constant E modifies H_t, our index of error level. We interpret E as the time required per bit of accuracy to sample initially encoded stimulus information, which sample is then transmitted to Stage 2 for central processing. As before, Stage 2 processing occurs at the rate given by the reciprocal of B in Eq. 4.

Thus, we have identified two steps to the Stage 1 operation: first, encoding into some kind of short-term store followed by a sampling of information from that store. As indicated in the discussion of Experiment II, Neisser (1967) has called the initial process in the encoding stage iconic storage and Sperling (1967) has proposed also a SCAN, recognition buffer memory mechanism for what we call here Stage 1. Therefore, our data and the above interpretation are entirely consistent with these theoretical concepts, and the present data support the usefulness of the SCAN component shown earlier in Figure 6.

From that model we may offer the following interpretation: (a) A stimulus appeared before the subject; (b) more information than needed was encoded at a rapid rate into iconic storage; (c) the SCAN mechanism sampled information from the icon at a rate approximating 6.4 bits per second; (d) since the subjects knew a priori the appropriate memory ensemble to be used (H_c = 1.0, 1.5, or 2.0), there was no need for the recognition buffer memory to assess the selected information but only to key the preordained ensemble for retrieval; (e) The necessary ensemble information was retrieved and compared to the sampled input information to seek a match, this Stage 2 activity occurring at a rate of about 9.2 bits per second; and (f) from the Stage 2 operations of match or no match, a response (yes or no) was selected and executed.

Our results, then, confirm Stone's (1960) prediction concerning the relationship of RT to H_c and error level. They also support the need for a sampling mechanism such as Sperling's (1967) SCAN and support thereby a model of human information processing that views such processing as a sequential series of identifiable and measurable components. It follows too that a statistical decision model, such as that advanced by Stone, appears a desirable choice to the deterministic models which have been proposed (see Smith, 1968). We will return to this latter point in the General Discussion section, below.

It is perhaps most important to note that these data indicate Hick's law as being manifested in Stage 1 of the Smith (1968) four-stage paradigm: In Eq. 5 the finding that RT is proportional to H_t is Hick's law. Therefore, in our present terms, Hick's law refers to the rate of gain of information through an input sampling operation.

Thus, Hick's law is a statement of sampling choice, not perceptual (identification) choice (Stage 2) or response choice (Stage 3), and Eq. 5 indicates that Hick's law is a component of a more general statement of additivity in human information processing.

EXPERIMENT IV
MEMORY RETRIEVAL AND CENTRAL COMPARISON TIMES IN INFORMATION PROCESSING[4]

Experiments II and III were successful in identifying two processes within Stage 1 of the sequential model shown in Figure 1. The present study looks to Stage 2 of that model to see if processes can be identified and measured there.

Sternberg (1968) presents a case for using the pattern of statistical interactions among independent variables to identify and name subprocesses in human information processing. Thus, if one uses independent variables F, G, and H in a choice reaction time task and finds that F, G, and H each exerted a statistically significant effect (main effects) on performance and that G and H interacted significantly, then it would follow that one could infer the presence of three subprocesses a, b, and c. It would follow also that Process a was influenced only by F while G and H influenced both Processes b and c. This in turn suggests that the temporal effects of F and G and of F and H are additive while those of G and H may not be.

This additive factors effect, as Sternberg calls it, is similar to the factor analysis procedure whereby one infers structure from the patterns of interrelations found in the data.

In the present study we manipulated four variables systematically: (a) memory loads of 1, 2, and 4 random figures, (b) display loads of 1, 2, and 4 random figures, (c) response mode—a positive or a negative response, and (d) practice in terms of blocks of daily sessions. The Sternberg Procedure II was used as in Experiment III, and the subjects were encouraged to make as few errors as possible.

From Sternberg (1968) we would expect to be able to identify up to three subprocesses, depending on the results, from the independent variables memory load, display load, and response mode. Further, the pattern of the effects of these variables on performance should determine the nature and extent of additivity in the data.

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[4] This study served as a MA thesis for Mr. John Blaha. It has been published in the Journal of Experimental Psychology, 1969, 79, March issue.

Method

Six males and six females served in this study for 13 sessions. All served under all conditions. On the first session each subject became thoroughly familiar with the seven random forms to be used in the Sternberg II task. Then on the second session and continuing through the 13th session, each subject viewed test slides of the figures and responded either "yes" a figure on the slide matches one in memory or "no" there is no match. Sixteen random figures defined the negative set and these matched the seven positive set figures in association value.

In a given session the subject worked under a single memory-load condition (ensembles of size 1, 2, or 4 figures) but he saw all three levels of display load a number of times. Under display load 1 a test slide contained a single random figure, two figues appeared side-by-side under display load 2, while four figures appeared in a 2×2 matrix in display load 4. No test slide contained more than one positive set figure, and half the slides contained only negative set figures while half contained a positive set figure. Across each three-session block each subject encountered each memory-load condition; thus, the experimental design was a 3 (memory load) × 3 (display load) × 2 (response mode—yes vs. no) × 4 (blocks of sessions).

Each subject experienced 192 trials per session but data from only the last 96 trials per session were analyzed, the first 96 trials being considered practice. Thus, Experiment IV provided very extensive practice with the random figures across the 12 sessions of data collection. Instructions emphasized both speed and accuracy, and a bonus system was introduced at the beginning of the second block of sessions which emphasized accuracy but which also rewarded the subjects for fast responses.

Results

Error levels were quite low in this task: Of the 72 cells in the design only 12 generated error levels greater than 2.5%. A median reaction time was calculated for each subject in each of the 72 cells of the design, and the 12 scores per cell then were subjected to an analysis of variance. All four main effects (memory load, display load, response mode, and practice blocks) were statistically significant at $p < .001$, and all first-order interactions, except blocks × response mode, were significant at $p < .05$ or better. Finally, the memory load × display load × response mode interaction was significant at $p < .01$, F (4, 792 df) = 3.61. This interaction is shown in Figure 10.

Three observations follow from Figure 10. First, the basic relationship between RT and memory load is not logarithmic; instead it is linear on a linear scale of memory load

$$RT = A + B\ (M) \qquad \text{Eq. 6}$$

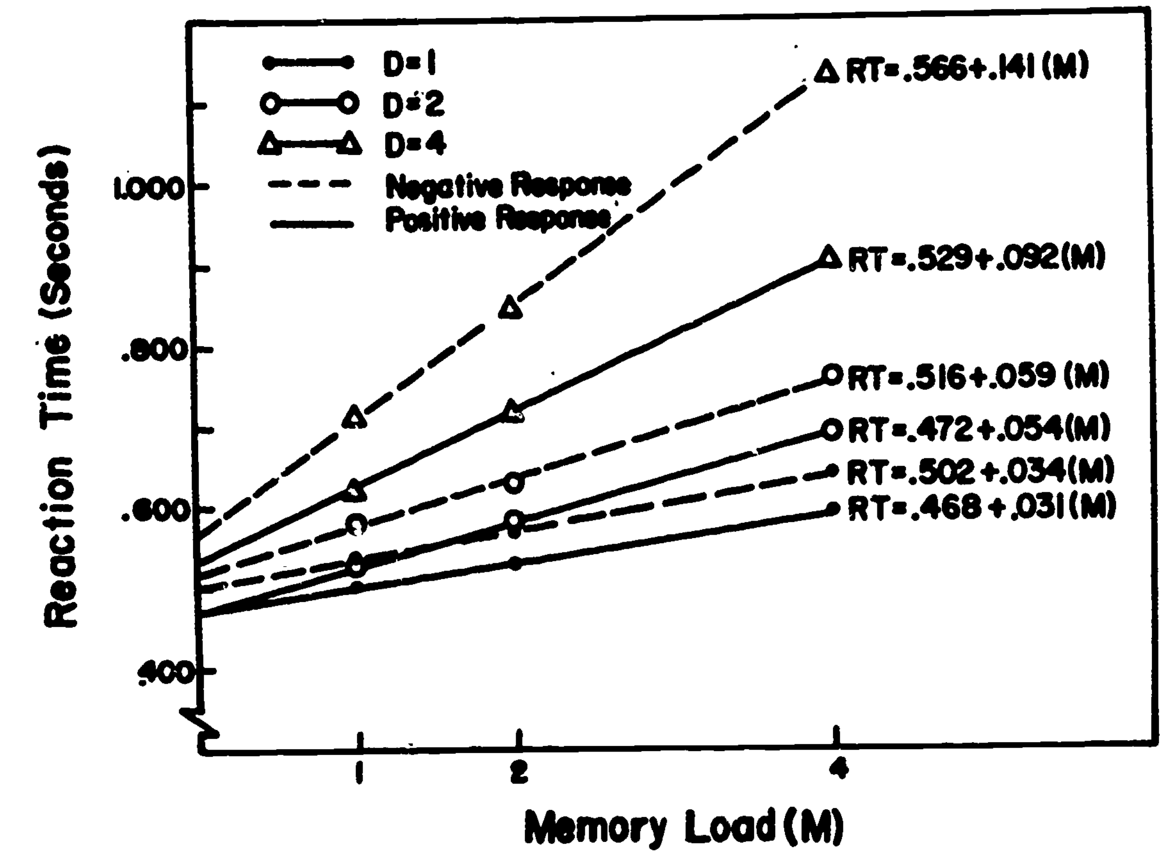

Fig. 10. The results averaged across blocks of Experiment IV.

where M is memory load (M = 1, 2, or 4 items). This is the same form of the Hick relationship noted in the initial test results of Experiment I in this series, and Sternberg (1966, 1967) has also obtained such a relationship in a comparable task using numerals as stimuli and as memory items.

Second, for the D = 1 and D = 2 conditions the positive responses were faster than the negative responses by a constant amount of 40 to 50 msec. This suggests that our subjects, like those of Sternberg (1966), engaged in an exhaustive comparison of encoded display information with memory items. For the D = 4 condition, however, there is a marked difference in slope of the two functions in Figure 10. While this could indicate a self-terminating comparison process in Stage 2 of our model (the subject stops searching memory when he finds a match but examines the entire memory ensemble when no match occurs), it is more likely that the two functions under the D = 4 condition represent the effect of a final check by the subjects under this highest display-load condition on those trials when there was no match between encoded and memory representations of stimulus information. In fact, during a formal debriefing at the end of the data collection period, the subjects volunteered the information that they did run a final check on display information prior to emitting a negative response under the D = 4 condition. Further, if the subject used a self-terminating strategy, the slope of the positive response function of the D = 4 condition should be half the slope of the negative response function

(Sternberg, 1967). Clearly, this is not the case. Therefore, it is concluded that under all three display-load conditions the subjects took 40 msec. or so longer to select a negative than to select a positive response (Stage 3) and that under D = 4 there also was a final check prior to a negative response which check certainly involved Stage 2 and probably Stage 1.

Finally, from Figure 10 it is apparent that the slope constant $\underline{B}$ (central processing time) is systematically related to display load for both the positive and the negative response data. Figure 11 summarizes the relationships here: For positive responses one finds that

$$B = F + G\,(D) \qquad \text{Eq. 7}$$

adequately defines the relationship between the slope constant $\underline{B}$ of the basic equation and display load (D). Further, $\underline{B}$ is a power function of display load for the negative response data:

$$B = F + G\,(D)^{H} \qquad \text{Eq. 8}$$

Therefore, if we substitute Eq. 7 as an identity for $\underline{B}$ in Eq. 6, we see that the following holds:

$$RT = A + F\,(M) + G\,(M)(D) \qquad \text{Eq. 9}$$

where M and D are memory and display load, respectively. The compar-

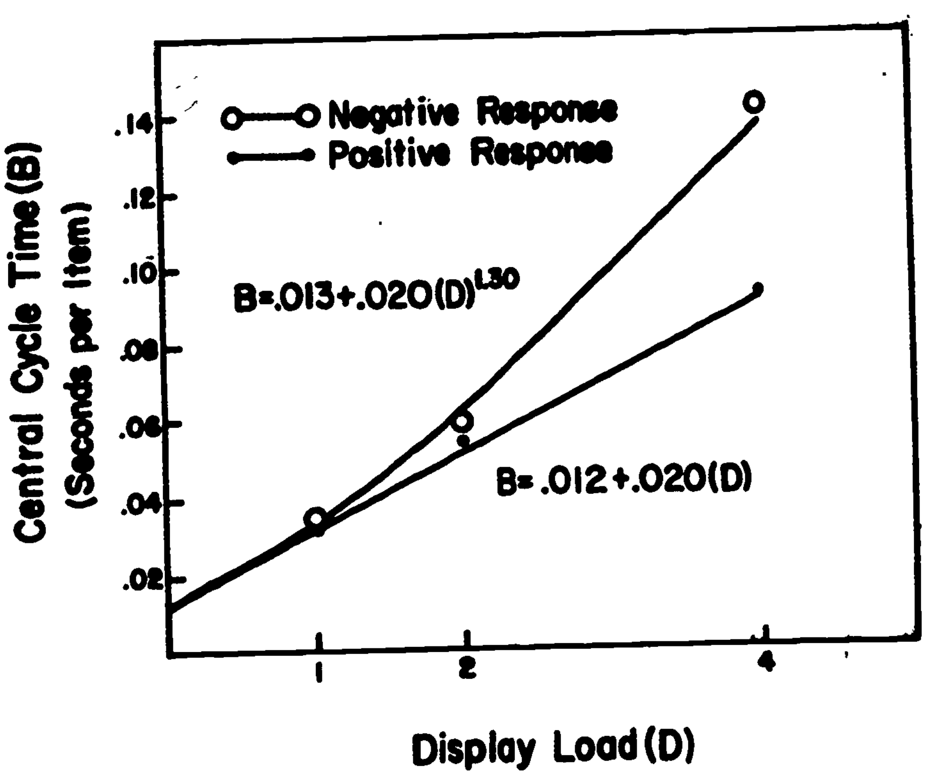

Fig. 11. The relationship between the slope constant of Equation 6 and display load in Experiment IV.

able equation for negative responses is

$$RT = A + F\ (M) + G\ (M)(D)^{H} \qquad \text{Eq. 10}$$

As fitted to the data of Figure 10, Eq. 9 yields

$$RT = A + .012\ (M) + .020\ (M)(D)$$

while Eq. 10 yields

$$RT = A + .013\ (M) + .020\ (M)(D)^{1.3}$$

Equations 9 and 10 were fitted also to the data for each of the four practice blocks. The best-fit constants are listed in Table 2 along with the maximum errors of prediction in seconds. Obviously, Eq. 9 and 10 provide good fits to the data.

Discussion

From Sternberg's paper (1968) it follows that the above results permit one to identify three components of the human information-processing system: Response mode effects illustrate the operation of a response-selection mechanism (Stage 3) while display load and memory load indicate by their interaction that two components of Stage 2 can be identified and measured, and the interaction of all three independent

Table 2

Best-Fit Equations Relating the Slope Constant B of Equation 6 to Display Load (D) for Each Block of Sessions in Experiment IV

Block		Maximum Error (Sec.)
	POSITIVE RESPONSES	
I	$B = .023 + .028\ (D)$	-.008
II	$B = .011 + .023\ (D)$	-.004
III	$B = .008 + .016\ (D)$	.000
IV	$B = .003 + .015\ (D)$	.000
	NEGATIVE RESPONSES	
I	$B = .026 + .027\ (D)^{1.31}$	.001
II	$B = .011 + .024\ (D)^{1.33}$	-.001
III	$B = .012 + .015\ (D)^{1.29}$	.014
IV	$B = .006 + .014\ (D)^{1.29}$	.006

variables leads to the checking operation in those cases where no match is found in Stage 2.

Note that in Eq. 9 the constant F is in units of seconds per item of memory. Its inverse is items of memory per second, which recommends the interpretation that F is memory retrieval time. Note also that in Eq. 9 the constant G is in units of secondsper item of memory per item of display. Its inverse, then, is comparisons per second which suggests that G is central comparison time. The same interpretation holds for Eq. 10 where one need add only that the power exponent H is an index of the final checking prior to a negative response.

Therefore, we may subdivide Stage 2 of our basic model into two component processes: memory retrieval and comparison operations. From Figure 10 we note that memory retrieval required 12 and 13 msec. for positive and negative responses, respectively, while the central comparison times of 20 msec. per comparison were obtained. These are average times across all 12 sessions (four blocks) of the study. Table 2 indicates that these memory retrieval and central comparison times decreased systematically as a function of practice. Figure 12 illustrates these trends.

From Figure 12 it is apparent that for each block of sessions memory retrieval time was faster than central comparison time. Further, memory retrieval time appears to be approaching zero (which would indicate continuously available memory information), while the central comparison times seem to be approaching an asymptote near 14 msec. per comparison. It would follow that central comparison time not memory retrieval time sets the upper limit of central processing rate.

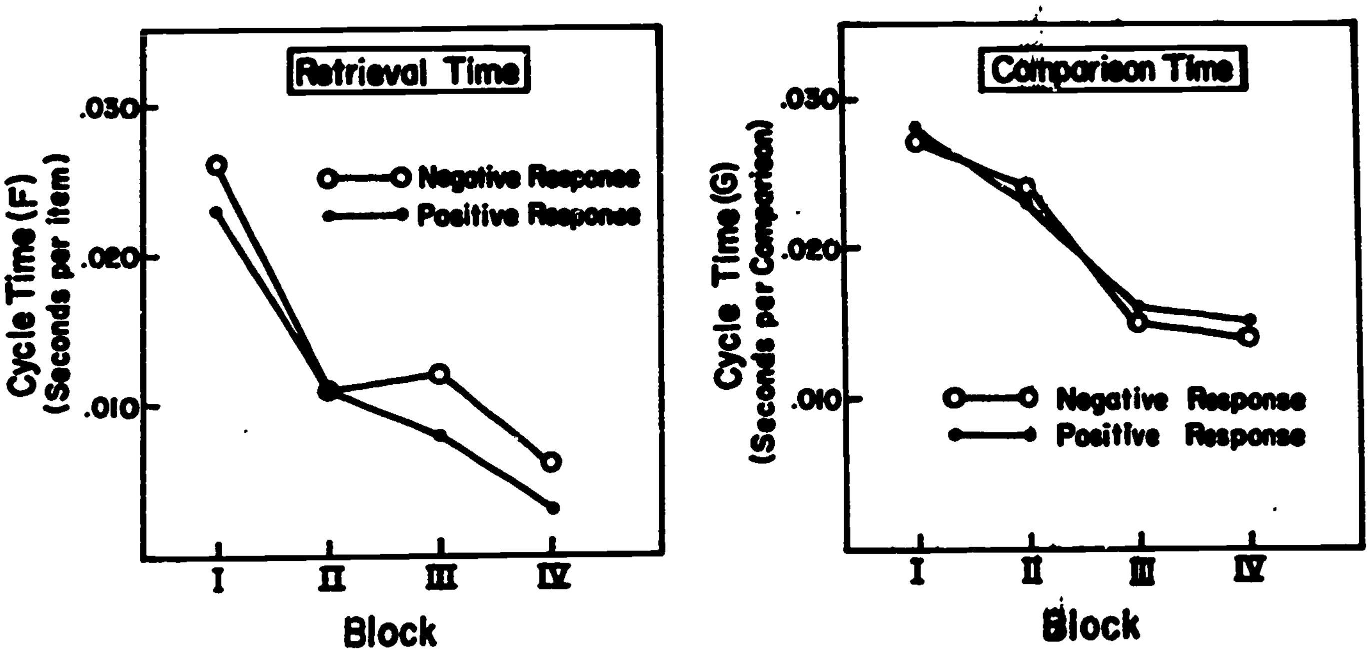

Fig. 12. Memory retrieval time and central comparison time as a function of practice (blocks) in Experiment IV.

From Figure 12 it is also clear that central comparison times for the positive and negative response trials were approximately equal. This is logical. However, on Block III, negative response trials showed a somewhat slower memory retrieval time than did positive response trials. It was considered likely that during Block III the subjects began to use directly information in memory concerning the negative set figures. This conclusion was supported by a short experiment conducted subsequent to the present study wherein after comparable amounts of practice another set of subjects recognized negative set stimuli with 96% accuracy when required to distinguish between those stimuli and other comparable figures never used in the previous sessions.

We may interpret the above results as follows: (a) A stimulus slide is presented. (b) The subject encodes displayed information, scans that short-term store, and loads the recognition buffer memory (Stage 1). (c) The appropriate memory ensemble is keyed by the recognition buffer memory and the items are retrieved at the rate of approximately 80 items per second (over all blocks); the comparison of encoded stimulus information and memorial representations occurs next at the average rate of 50 comparisons per second; and if a match occurs under any display load, the subject proceeds to Stage 3; however, if no match occurs under $D = 4$, a final rapid check is made to verify this outcome (Stage 2). (d) Following the comparison process and any checking required, the subjects selects a response (Stage 3), and (e) that response is emitted (Stage 4). Stage 3 requires approximately 40 msec. longer for a negative than a positive response.

GENERAL DISCUSSION

In each of the four experiments cited above a Hick relationship was found to hold either in the form

$$RT = A + B\ (H_c) \qquad \text{Eq. 3}$$

or in the form

$$RT = A + B\ (M) \qquad \text{Eq. 6}$$

where H_c is a Shannon (1948) measure of the uncertainty associated with Stage 2 or central processing of information and M is memory load. Under an interpretation that Stage 2 consists of a sequence of comparisons of encoded stimulus information with memorial representations of possible (positive set) stimuli, both H_c and M are indices of the number of such steps or comparisons required to identify the stimulus and thereby to determine the response.

Therefore, these experiments join many others in their testimony to the generality of a Hick relationship (see Smith, 1968, for a review of this area). Where the present experiments are unique is in showing that subprocesses can be separated out from both the intercept constant A (Experiments II and III) and the slope constant B (Experiment IV). Further, Experiments II, III, and IV showed that the subprocesses so identified can also be measured in their average time durations. Thus, the present studies represent a significant expansion of Eq. 3 to more analytic forms.

Across Experiments II, III, and IV we may infer that the additivity statement may be expanded from the form

$$RT = A + B\,(M) \qquad \text{Eq. 6}$$

to the statement

$$RT = C + E\,(S) + F\,(RBM) + G\,(M) + H\,(M \times D) \qquad \text{Eq. 11}$$

for positive responses where C is encoding time plus decoding time, E is input scan (S) time (Experiment III), F is time required by the recognition buffer memory (RBM) to perform preprocessing of the sample of encoded stimulus information available and thereby signal the proper memory ensemble for retrieval (Experiment II), G is memory (M) retrieval time, and H is central comparison time where memory load (M) times display load (D) determine the number of comparisons required (Experiment IV).

The constants C, E, and F of Equation 11 are contained within the constant A of Eq. 6 while the constants G and H of Eq. 11 are components of the constant B of Eq. 6. Admittedly, no one experiment in the present series examined more than two of the component processes; however, it is believed that the suitably designed study would provide valid measures of all five component time constants in Eq. 11.

It may also be noted that the intercept constant C of Eq. 11 could be further subdivided. In the present statement C is encoding (iconic storage) plus decoding (response selection). If one introduced an independent variable which influenced response selection directly, then such an effect should permit the measurement of a time constant for response selection which should be independent of and additive to the time for the encoding process.

From Eq. 11, then, we may represent the sequential model of human information processing in a more complete form than that provided earlier in Figure 1. This has been done in Figure 13, below. It is believed that Figure 13 covers in a parsimonious manner all of the effects noted in the present series of experiments plus those noted elsewhere by researchers such as Sternberg (1967) and Sperling (1967), among others.

As shown, information flow is from left to right with each component feeding information to the succeeding stage or component. Note that the recognition buffer memory (RBM) is shown with two output

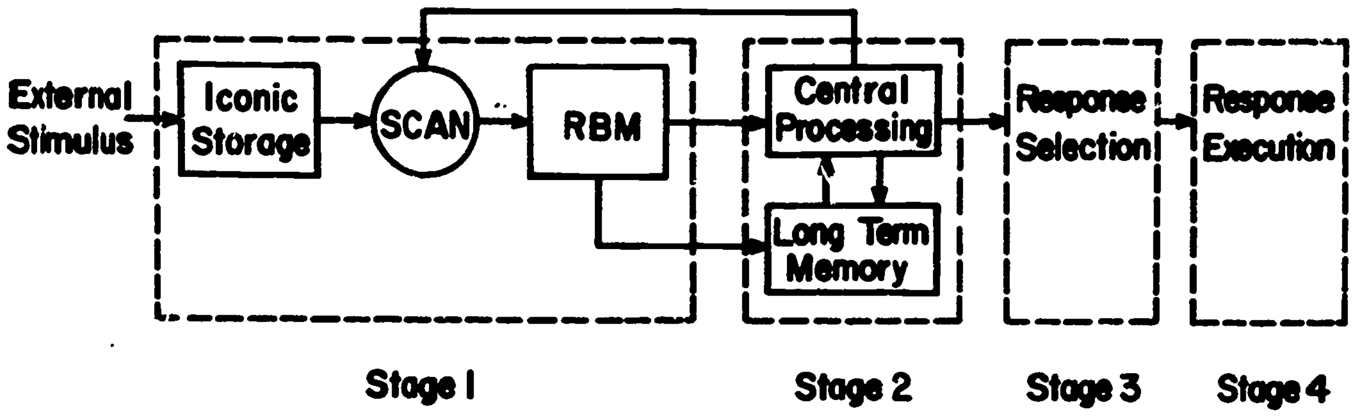

Fig. 13. An expanded model of human information processing. RBM refers to a recognition buffer memory.

channels: The top channel feeds the central processor with encoded and sampled stimulus information, while the bottom channel serves to key the appropriate ensemble from long-term memory for retrieval into the central processor or working memory. Note also the feedback loop from the central processor to the SCAN mechanism. This feedback loop is indicated both by Experiment III as a means to call for more information under accuracy conditions and by Experiment IV to perform a final check prior to emitting a negative response under heavy display-load conditions. Parenthetically, the same feedback loop could serve as a rehearsal loop as in Sperling's task (1967).

Conclusions

The results noted herein are consistent with the view that man is a sequential processor of information. That is, there is a sequence of processing steps and stages which can be measured individually. Further, Donders' additivity principle (1868) seems to hold such that either Eq. 3 or Eq. 6 can be expanded to obtain an expression relating total reaction time to the times of the individual components or processes.

The subjects appear to perform Stage 2 operations in a sequential as contrasted with a parallel mode. That is, each encoded representation is compared either one-by-one with the memorial representations or in a more sophisticated dichotomous manner. Further, such comparison or testing is exhaustive, not self-terminating.

The processing rates for the Stage 2 operations become very high with practice. Memory retrieval rates, as measured in Experiment IV, increased from an initial rate of 43 items per second to a rate over 300 items per second by the end of the data collection period. The latter rate suggests that memory items were becoming continuously available to a working memory rather than being retrieved from long-term memory for transfer in a working memory. The comparison operation (presumably involving working memory) initially proceeded at a rate of 36 comparisons per second and increased to 67 comparisons per second by the end of Experiment IV. It is concluded that the comparison operation rather than memory retrieval sets the upper limit for the rate of processing information through Stage 2.

From Experiment III it follows that the sampling-buffer memory time for the SCAN-RBM mechanisms (see Figure 13) is somewhat slower than the total processing rate of Stage 2: Our estimate of SCAN-RBM rate is 6.4 bits per second while that for central processing is 9.2 bits per second (see the data fit for Eq. 5 of Experiment III). This faster rate for a subsequent stage (Stage 2) is consistent with the feedback loop from Stage 2 to the SCAN mechanism of Stage 1 in Figure 13: The central processor can determine the need for additional input information rather quickly and so signal the sampling mechanism whose slower rate then need not penalize total reaction time. This in turn suggests that the functions performed by the SCAN mechanism and the recognition buffer memory, while slower than the central processor, permit the latter to be relatively fast by formating or other preprocessing activities. Future research could profitably examine the recognition buffer functions in particular. From Experiment II it is clear that ensemble recognition is one function of the recognition buffer memory, and Sperling (1967) suggests that the buffer can select rehearsal routines. What other functions, such as formating, may also be identified?

The above research indicates that we are beginning to obtain rather analytic insights to man as an information processor. Not only is the methodology capable of identifying logically related component processes, but also it has been demonstrated that one can quantify the rates of such processing steps. The key to this methodology is the selection of independent variables such as display load and particularly memory load which influence subprocesses in an additive manner. Quantitative variation across each independent variable differentially loads particular subprocesses and thereby avoids the trap in which Donders (1868) fell: attempting to obtain processing times by the use of qualitatively different tasks.

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